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On the optimal control of carbon dioxide emissions: an application of *FUND*

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This paper presents the *Climate Framework for Uncertainty, Negotiation and Distribution* (*FUND*), an integrated assessment model of climate change, and discusses selected results. *FUND* is a nine-region model of the world economy and its interactions with climate, running in time steps of one year from 1990 to 2200. The model consists of scenarios for economy and population, which are perturbed by climate change and greenhouse gas emission reduction policy. Each region optimizes its net present welfare. Policy variables are energy and carbon efficiency improvement, and sequestering carbon dioxide in forests. It is found that reducing conventional air pollution is a major reason to abate carbon dioxide emissions. Climate change is an additional reason to abate emissions. Reducing and changing energy use is preferred as an option over sequestering carbon. Under non-cooperation, free riding as well as assurance behaviour is observed in the model. The scope for joint implementation is limited. Under cooperation, optimal emission abatement is (slightly) higher than under non-cooperation, but the global coalition is not self-enforcing while side payments are insufficient. Optimal emission control under non-cooperation is less than currently discussed under the Framework Convention on Climate Change, but higher than observed in practice.

Keywords: integrated assessment of climate change, optimal control, game theory, secondary benefits

1. Introduction

This paper asks the questions whether and (if so) how much and where to abate anthropogenic greenhouse gas emissions, so as to limit climatic change. Of course, these questions are not answered, but some insights are generated by applying the *Climate Framework for Uncertainty, Negotiation and Distribution*, version 1.5. The insights obtained are limited by this integrated assessment model, not only in the sense that the insights do not consider what is not in the model, but also in the sense that the insights are only valid for the part of the assumption space explored by the model. These limitations are partly lifted by complementing the model's outcomes with findings in the literature.

FUND is classified by the IPCC (Weyant et al. [35]) as a 'policy optimization' model, that is, an integrated assessment model (IAM) that advices policy makers what an optimal climate policy looks like, rather than evaluating the consequences of proposed policies. Three prominent IAMs of this type are *CETA* (Peck and Teisberg [21–25]), *DICE* (Nordhaus [17–19]) and *MERGE* (Manne and Richels [16], Manne et al. [15]). *FUND* deviates in a number of ways from these models. Firstly, *FUND*'s economic module is simpler even than *DICE*'s, in order to allow uncertainty analysis (the topic of a future paper). *FUND*'s greenhouse gas emission (reduction) module is comparable to *DICE*'s, and thus simpler than *CETA*'s and *MERGE*'s. Secondly, the climate impact module of *FUND* is more complex than the other models'. The most important differences are that, in *FUND*, impacts depend, to a large extent, on the rate of climate change and on vulnerability of climate change (a function of mainly per capita income). The time profile and extent of impacts is very different in *FUND*. Thirdly, *FUND* includes no-regret measures for economic and environmental measures while the other models define this away by readjusting their baseline scenarios. Fourthly, *FUND* solves optimal emission control for more regions both cooperatively and non-cooperatively. To date, similar results have only been reported for *RICE* (Nordhaus and Yang [20]), although the other modelling teams are working on this. More analytical treatments of greenhouse games can be found in Eyckmans et al. [3], Fankhauser and Kverndokk [4] and Hoel [5–8]).

Section 2 briefly describes the model. Section 3 runs *FUND* in its basic settings, using best guesses for socio-economic development, climate change, impacts and costs of emission reduction. *FUND* is capable of running in eight different optimization modes (top-down vs. bottom-up; cooperative vs. non-cooperative; with vs. without inter-regional capital transfers), the results of which are discussed in section 3. Section 4 analyzes how sensitive these results are to plausible variations of the assumptions on parameters. Section 5 concludes by revisiting the questions asked above, and by outlining future research.

2. Model description

Figure 1 presents the flow diagram of *FUND*. Tol [33] gives a full equation-by-equation description of the model,

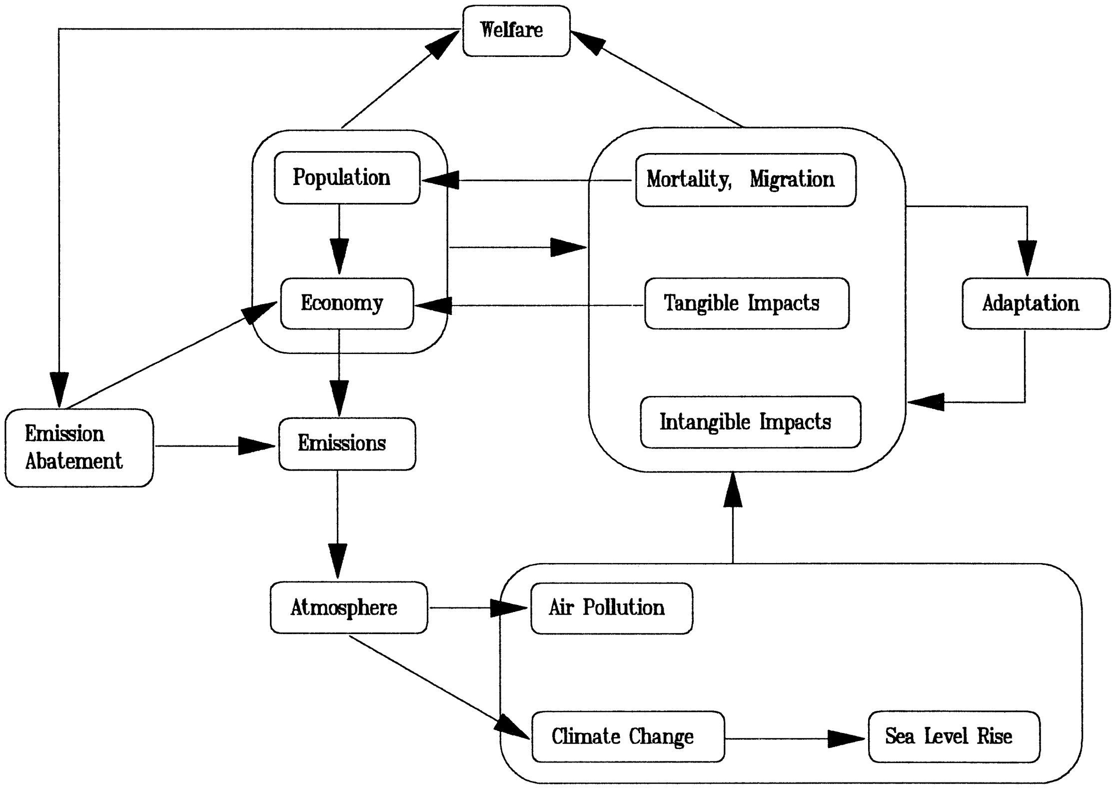

Figure 1. Flow diagram of the *Climate Framework for Uncertainty, Negotiation and Distribution*, version 1.5.

which is available from the author upon request. Tol [34] gives a detailed analysis of the climate change impact module. Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations, specified for nine major world-regions, defined in table 1. The model runs from 1990 to 2200, in time steps of a year.

2.1. Exogenous forces

The exogenous scenarios concern the rate of economic growth, the population growth, autonomous energy efficiency improvements, the rate of decarbonization of the energy use (autonomous carbon efficiency improvements), and methane and nitrous oxide emissions.

2.1.1. Population

Regional population growth is based on the Worldbank's population projections (Bulatao et al. [2]). Population falls with climate change deaths, resulting from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to affect only the elderly, non-reproductive population; heat stress only affects urban population. The share of urban in total population is, up to 2025, based on the World Resources Databases; after 2025, urban population slowly converges to 95% of total population. Population also changes with climate-induced migration between the regions.

2.1.2. Economy

Gross regional product (GDP) per capita income grows exogenously according to the standardized scenario of the Energy Modeling Forum Round 14: Integrated Assessment of Climate Change, which is close to the IS92a scenario of the IPCC (Leggett et al. [14]). Each year, consumption (75%) and investment (25%) are lowered by the tangible impacts of climate change. Consumption and investment are also lowered by the tangible impact of conventional air pollution, and by the spendings on greenhouse gas emission reduction.

2.1.3. Energy and emissions

Total energy use grows with GDP and falls with the (exogenous) autonomous energy efficiency improvement (AEEI) and the policy induced energy efficiency improvement. Carbon dioxide emissions grow with total energy use and fall with the exogenous autonomous carbon efficiency improvement (ACEI) and policy induced carbon efficiency improvement. The sum of AEEI and ACEI roughly matches the AEEIs of the EMF14 standardized scenario. Carbon dioxide emissions from land use changes follow the IPCC IS92a scenario (Leggett et al. [14]), but can be reduced by policy intervention.

2.2. Endogenous variables

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, the impact of

Table 1
Regions of the *Climate Framework for Uncertainty, Negotiation and Distribution*.

Region (acronym)	Description
OECD-America (OECD-A)	Canada, USA
OECD-Europe (OECD-E)	European Union, Norway, Iceland, Malta, Switzerland, Turkey, Israel
OECD-Pacific (OECD-P)	Japan, Australia, New Zealand
Central and Eastern Europe and the former USSR (CEE&fSU)	Poland, former Chzechoslovakia, Hungary, Bulgary, Romania, Albania, former Yugoslavia, former Soviet Union
Middle East (ME)	Asian-Arabic countries, Iran
Latin America (LA)	South and Middle America, Caribbean
South and Southeast Asia (S&SEA)	Rest of Asia and Oceania, stretching from Afghanistan to Papua New Guinea, including archipalogo nations in Indian and Pacific oceans
Centrally Planned Asia (CPA)	China, Laos, Mongolia, Vietnam, North Korea
Africa (AFR)	Africa

Table 2
Monetized estimates of the impact of global warming (in 10^9 US$).

Region	Species	Life	Agric.	Sea	Extreme	Total
Level (global mean temperature: +2.5°C; sea level: +50 cm; hurricane activity: +25%; winter precipitation: +10%; extratropical storm intensity: +10%)						
OECD-A	0.0	−1.0	−5.3	0.9	2.5	−2.9
OECD-E	0.0	−1.1	−6.0	0.3	0.3	−6.5
OECD-P	0.0	−0.5	−6.1	1.5	5.5	0.3
CEE&fSU	0.0	3.7	−23.2	0.1	0.2	−19.1
ME	0.0	3.5	3.1	0.1	0.0	6.6
LA	0.0	67.0	7.3	0.2	0.0	74.5
S&SEA	0.0	81.4	15.8	0.2	0.6	98.8
CPA	0.0	58.4	−22.2	0.0	0.1	36.3
AFR	0.0	22.5	5.4	0.1	0.0	28.0
Rate (global mean temperature: 0.04°C/year; other variables follow)						
OECD-A	0.3	0.2	0.3	0.2	0.2	1.2
OECD-E	0.3	0.2	0.0	0.2	0.0	0.7
OECD-P	0.2	0.1	0.0	0.3	0.4	1.0
CEE&fSU	0.1	0.1	0.0	0.0	0.0	0.2
ME	0.0	0.0	0.1	0.0	0.0	0.2
LA	0.0	0.4	0.1	0.1	0.0	0.6
S&SEA	0.0	0.3	0.1	0.1	0.0	0.6
CPA	0.0	0.2	0.3	0.0	0.0	0.5
AFR	0.0	0.0	0.1	0.0	0.0	0.2

carbon dioxide emission reductions on economy and emissions, and the impact of the damages of climate change on the economy and the population.

2.2.1. Atmospheric composition

Greenhouse gases are taken up in the atmosphere, and then geometrically depleted; life-times are taken from Titus and Narayanan [31]. Industrial carbon dioxide is exogenous. Carbon dioxide from land use change, methane and nitrous oxide follow exogenous emission scenarios (based on IS92a).

2.2.2. Climate change

Radiative forcing for carbon dioxide, methane and nitrous oxide are based on Shine et al. [30]. *FUND* calculates sea level, hurricane activity, winter precipitation, and winter

Table 3
Duration of damage memory per category.[a]

Category	Years	Category	Years
Species loss	100	Immigration	5
Agriculture	10	Emigration	5
Coastal protection	50	Wetland (tangible)	10
Life loss	15	Wetland (intangible)	50
Tropical cyclones	5	Dryland	50

[a] Damage is assumed to decline geometrically such that after the displayed life-time only one per cent of the initial damage remains.
Source: Tol [33].

storm activity because these feed into the damage module. However, these factors depend linearly on the global mean temperature. In the current model version, this is merely accounting; a future version of the model will improve on this. A future version will also investigate the influence of sulphate aerosols (a regional climate effect) on optimal regional greenhouse gas emission reduction. The climate module of *FUND* is calibrated to mimic the outcomes of more complex models. In the base case, global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents. *FUND*'s temperature profile over time is also typically as can be found for the IS92a scenario in the last IPCC report (Kattenberg et al. [12]).

2.2.3. Climate impact

A limited number of categories of the impact of climate change is considered. The damage module has two units of measurement: people and money. People can die (heat stress, malaria, tropical cyclones), not die (cold stress), or migrate. These effects, like all impacts, are monetized. Damage can be due to either the rate of change (benchmarked at 0.04°C/yr) or the level of change (benchmarked at 2.5°C). Damage in the rate of temperature change slowly fades at a speed indicated in table 3. Damage is calculated through a second-order polynomial in climatic change. Damage is distinguished between tangible (market) and intangible (non-market) effects. Tangible damages affect investment and consumption; through investment, economic growth is affected; through consumption, welfare is affected. Intangible damages affect welfare. Relative vulnerability to climate change changes with economic development in many ways. The importance of agriculture falls with per capita income growth, and so do malaria incidence and the inclination to migrate. Heat stress increases with urbanization. The valuation of intangible increases with per capita income.

2.2.4. Emission reduction

Two ways to reduce carbon dioxide emissions are treated: energy and carbon efficiency improvement, and forestry measures. The impact of policies to reduce carbon dioxide emissions from energy use is twofold. On the one hand, technology is changed by the intervention, so that (i) the amount of energy needed to produce one dollar is (permanently) lowered; and (ii) the amount of carbon dioxide emitted to produce one joule of energy is (permanently) lowered. On the other hand, economic growth or economic output is lowered, depending on whether *FUND* uses its top-down or bottom-up parameterization. The main difference between top-down and bottom-up is the cost function. In both cases, the reduction cost function is quadratic, but, in the top-down parameterization, reduction costs are much higher. Top-down models by and large reflect an economist's view of the energy system. Such models typically assume that energy is currently supplied in an optimal way (i.e., at minimum costs); therefore, emission reduction is expensive. Bottom-up models by and large reflect an engineer's view of the energy system. Such models typically assume that moving energy supply to the technological frontier would reduce emissions while saving money; therefore, emission abatement is cheap, if not beneficial. See Hourcade et al. [9] for a more thorough discussion. Table 4 displays the parameters for the top-down cost function. Table 5 displays the parameters for the bottom-up cost function. An energy and carbon efficiency improvement programme imposes a measure in 1990, and maintains it at this level for a period of 10 years. After 10 years, the measure is increased with the same amount as in 1990. This procedure is repeated 6 times. In this manner, emission reduction is controlled by one parameter so that an optimum can readily be found. The value of the most important policy variable – emission control in the 1990s – is hardly affected by this simplification.

2.2.5. Secondary benefits

Besides emission reduction and economic costs, *FUND* also considers the secondary benefits, i.e., reduced conventional air pollution. Secondary benefits are linear in emissions. Air pollution damage is defined in deviation from the present. The parameters can be found in table 6. The damage coefficient falls over time with the autonomous energy and carbon efficiency improvements.

2.2.6. Afforestation

Forestry measures lead to a direct uptake of carbon dioxide. The costs of afforestation are assumed to be quadratic in the amount of carbon sequestered. The parameters can be found in table 7. The costs of slowing deforestation are assumed to equal two-thirds of those of afforestation. Slowing deforestation is constrained by deforestation. Afforestation and slowing deforestation are implemented in a cost-effective manner. An afforestation programme absorbs a certain, fixed amount of carbon over sixty years.

2.3. Optimization

2.3.1. Objective function

The costs of emission reduction are weighted against the avoided damage of climate change. The criterion is the net present value of average utility, a mixture of per capita income, tangible and intangible damage of climate change

Table 4
Parameters of cost function for CO_2 emission reduction, top-down studies.

Region	α^T	β^T	1% red.[a]	10% red.[b]
OECD-America[c]	0.0134	0.6296	0.02	0.76
OECD-Europe[d]	0.0367	0.4081	0.04	0.77
OECD-Pacific[d]	0.0542	0.4262	0.06	0.97
Central and Eastern Europe and the former Soviet Union[e]	0	1.6335	0.02	1.63
Middle East[f]	0.0097	0.4982	0.01	0.60
Latin America[g]	0	12.0296	0.12	12.03
South and South-East Asia[g]	0	3.8450	0.04	3.85
Centrally Planned Asia[h]	0.0093	0.4655	0.01	0.56
Africa[i]	0.0097	0.4982	0.01	0.60

[a] Total costs (as per cent of GDP) of a one per cent cut in carbon dioxide emissions.
[b] Total costs (as per cent of GDP) of a ten per cent cut in carbon dioxide emissions.
[c] Best fit on IPCC estimates (Hourcade et al. [9]).
[d] Best fit on IPCC estimates (Hourcade et al. [9]).
[e] Best fit on IPCC estimates (Hourcade et al. [9]).
[f] Assumed equal to Africa.
[g] Second order Taylor approximation around zero of cost curve of Rose and Stevens [27].
[h] Best fit on IPCC estimates (Hourcade et al. [9]).
[i] China cost curve adjusted so as to reflect the claim of Rose and Stevens that costs in Africa and China are the same, in absolute terms, per tonne of carbon.

Table 5
Parameters of cost function for CO_2 emission reduction, bottom-up studies.

Region	α^S	β^S	1% red.[a]	10% red.[b]
OECD-America[c]	−0.0100	0.1700	−0.01	0.07
OECD-Europe[d]	−0.0100	0.1700	−0.01	0.07
OECD-Pacific[d]	−0.0100	0.1700	−0.01	0.07
Central and Eastern Europe and the former Soviet Union[e]	−0.0035	0.1700	0.00	0.14
Middle East[f]	−0.0073	0.9546	0.00	0.88
Latin America[g]	−0.0073	0.9546	0.00	0.88
South and South-East Asia[g]	0.0093	0.2180	0.01	0.31
Centrally Planned Asia[h]	0.0093	0.2180	0.01	0.31
Africa[f]	−0.0073	0.9546	0.00	0.88

[a] Total costs (as per cent of GDP) of a one per cent cut in carbon dioxide emissions.
[b] Total costs (as per cent of GDP) of a ten per cent cut in carbon dioxide emissions.
[c] Best fit on IPCC estimates (Hourcade et al. [9]).
[d] Assumed equal to OECD-America.
[e] Best fit on IPCC estimates (Hourcade et al. [9]).
[f] Assumed equal to Latin America.
[g] Best fit on IPCC estimates (Hourcade et al. [9]).
[h] Assumed equal to South and South-East Asia.

and air pollution, and emission reduction costs. Yearly welfare follows

$$W_{j,t} = \ln\left(\frac{Y_{j,t} - D^{\mathrm{Int}}_{j,t} - L^{\mathrm{Int}}_{j,t}}{P_{j,t}}\right) = \ln\left(\frac{Y_{j,t}}{P^{p}_{j,t}}\right) + \ln(1-\Omega_{j,t}) \approx \ln\left(\frac{Y_{j,t}}{P_{j,t}}\right) - \Omega_{j,t} - \frac{1}{2}\Omega^2_{j,t}, \tag{1}$$

where

$$\Omega_{j,t} = \frac{L^{\mathrm{Int}}_{j,t} + D^{\mathrm{Int}}_{j,t}}{Y_{j,t}} \tag{2}$$

with $W_{j,t}$, the welfare of region j in year t, Y, gross domestic product, P, total population, L^{Int}, the intangible costs of global warming, and D^{Int}, the intangible costs of air pollution. Welfare is standard – natural logarithm of per capita income[1] – in its tangible attributes, but only

[1] Note that the savings' rate is constant.

Table 6
Marginal secondary benefits of carbon emission reduction.

Region	Tangible ($/tC)	Intangible ($/tC)	Total ($/tC)	Doubling[a] (% GDP)
OECD-A	7.50	7.50	15.00	0.42
OECD-E	6.22	4.96	11.18	0.25
OECD-P	1.93	2.09	4.02	0.05
OECD	6.30	5.83	12.13	0.27
CEE&fSU	6.13	3.33	9.46	0.39
ME	0.45	0.11	0.56	0.25
LA	1.44	2.25	1.69	0.06
S&SEA	2.11	0.12	2.23	0.11
CPA	3.07	0.14	4.01	0.69
AFR	0.93	0.06	0.99	0.04
non-OECD	2.73	0.96	3.69	0.29
World	4.16	2.91	7.07	0.27

[a] The cost (tangible and intangible) a doubling of fossil fuel use would have, under the assumptions that the marginal damage and emission coefficients are constant.

Table 7
Afforestation cost parameters.

Region	Constant (α) (1000$)	Linear (β) (1000$/tC)	Square (γ) (1000$/tC^2)
OECD-America	0.005	−0.0333	0.00062
OECD-Europe	0.007	−0.0467	0.00056
OECD-Pacific	0.004	−0.0267	0.00042
Central and Eastern Europe and the former Soviet Union	0.007	−0.0467	0.00049
Middle East	0.003	−0.0205	0.00626
Latin America	0.002	−0.0133	0.00006
South and South-East Asia	0.002	−0.0133	0.00003
Centrally Planned Asia	0.003	−0.0200	0.00020
Africa	0.002	−0.0075	0.00007

approximately so in the intangibles. The specification is the second order Taylor approximation of $\ln(1-\Omega)$. An approximation is used because it cannot be excluded that $\Omega > 1$, rendering utility unbounded if using the natural logarithm. $\Omega > 1$ would obtain if the monetary value of the intangible impacts exceeds income[2] in a particular year, for instance if more than 0.5% of the population dies from climate change. Such an extreme case could occur in an uncertainty analysis; attaching a welfare of minus infinity to this situation would lead expected welfare to be minus infinity as well, no matter how small the chance that this occurs.[3]

Net present welfare is

$$\mathrm{NPW}_j = \sum_{t=1990}^{2200} W_{j,t}(1+\rho_j)^{1990-t}. \qquad (3)$$

The discount rate ρ reflects the pure rate of time preference. The discount rates are set to 1% per year for all regions; 1% is low from an economic perspective, but high from a sustainability perspective (cf. Arrow et al. [1]). The discount rates are fixed over time in order to reflect the interests of present-day decision makers.

[2] There is little reason to restrict monetized welfare loss to ability to pay.
[3] In *FUND*, version 1.4, this was observed (Tol et al. [32]).

2.3.2. Solutions and algorithms

FUND optimizes in eight modes. Firstly, the costs of emission reduction can be specified with a top-down or a bottom-up parameterization. Secondly, regions can cooperate or not. In the non-cooperative case, a Nash–Cournot solution is calculated iteratively. The starting point is unilateral action. Each region then learns of the other regions' plans and adjust its policy. Next, each region learns of the adjusted plans, and so on, until an equilibrium is reached. Convergence is acheived in all cases, and rapid in most. In the cooperative case, global welfare is defined as the sum of the regional welfares.[4] Thirdly, optimizations can be carried out with and without interregional capital transfers.

[4] In a robustness analysis, global welfare was specified as the product of regional welfare (Bernoulli–Nash), and similar to regional welfare using global income and population as inputs. Optimal control is little sensitive to this.

Remember that all variables of *FUND* are either directly or indirectly determined by exogenous scenarios – no optimization is required to calculate the business as usual scenario (or any other scenario). Greenhouse gas emission control is the only variable that is optimized. The solution technique is a fancy grid search, where the fanciness lies in the variable step-size and the stopping rule, which assumes that there is a unique optimum.[5]

2.3.3. Interregional capital transfers

The regions interested in greenhouse gas emissions not necessarily coincide with the regions where this may be achieved in the cheapest or most effective manner. Therefore, interregional capital transfer may contribute to emission abatement. This is modelled in the following way. First, all regions are assumed to have implemented the measures according to the non-cooperative game described above. This is in the spirit of the Framework Convention on Climate Change, which states that measures implemented in a foreign country are not to replace national emission reductions. Note that this is not necessarily an efficient solution.

Each region then evaluates additional abatement measures. If a measure shows to be beneficial, i.e., increasing the region's own net present welfare, it is implemented. Otherwise, a 'price' X (equal to the net present welfare without the measure minus the net present welfare with the measure) is attached to it. This 'price' equals the net present welfare of capital transfer K, so

$$\begin{aligned} X &= \sum_{t=1990}^{2200} \frac{1}{(1+\delta)^t} \left(\ln\left(\frac{(Y_{1990}+K)(1+g_{1990})^t}{P_{1990}(1+p_{1990})^t} \right) \right. \\ &\qquad \left. - \ln\left(\frac{Y_{1990}(1+g_{1990})^t}{P_{1990}(1+p_{1990})^t} \right) \right) \\ &= \ln\left(1+\frac{K}{Y_{1990}}\right) \sum_{t=1990}^{2200} \frac{1}{(1+\delta)^t}, \end{aligned} \tag{4}$$

where Y_{1990} denotes the gross regional product in 1990 and g its growth, and P_{1990} total population in 1990 and p its growth rate (note that 1990 growth rates are used only for notational convenience – the crucial assumption is that capital transfers do not influence economic growth rates). This leads to

$$K = Y_{1990}\left(e^{X/88.6} - 1\right). \tag{5}$$

Next, all measures plus the associated capital transfers of all regions are offered to the clearinghouse and evaluated by all regions. The evaluation is based on the net present welfare of the investing region which transfers an amount of capital equal to K to the receiving region which implements the emission reduction; the evaluation of the bidder is also based on (5). The (hypothetical) auctioneer grants the transfer right to the region with the highest welfare gain. If this gain is positive, the transfer is implemented. Otherwise, it is not.

Interregional capital transfers can also be evaluated in the cooperative case. Emission reduction measures are first evaluated without interregional capital transfers. Global welfare is optimized. Next, the winners from cooperation compensate the losers; the winners pay proportional to their gain. The bilateral capital transfers of the non-cooperative game are thus transformed to multilateral capital transfers. It may of course happen that the capital transfers prove not to be sufficient to offset welfare losses in some regions – this is the case if poorer regions (where additional income has a relatively high additional welfare) are to transfer capital to the richer regions (where additional income has a relatively low additional welfare).

3. Base case results

This section discusses the outcomes of *FUND* under best guesses for all parameters. Sensitivity analyses are the topic of the next section. Uncertainty analyses and a discussion of the robustness of *FUND* to changes in its functional specification are postponed to future papers.

3.1. Business as usual

The business as usual scenario consists of three parts: (i) the potential growth of population and economy, as exogenously defined above, and the resulting carbon dioxide emissions; (ii) the corresponding damage from conventional air pollution; and (iii) the corresponding climate change and its impacts. It is important to distinguish between these three components because of the feedback of damage on population and economy. Remember that the business as usual scenario does not require any optimization.

Population is assumed not to be affected by conventional air pollution. With climate change added, heat stress, malaria and emigration reduce population; cold stress and immigration increase population. In the OECD, Eastern Europe and the former Soviet Union, climate change leads on balance to some additional population growth; in the other regions, population grows a little less because of climate change.

Figure 2 displays per capita income (potential, potential including air pollution, and potential including air pollution and climate change) in OECD-Europe and South and South-East Asia. Air pollution and climate change have significant impacts on economic development, particularly in the poorer regions. Nevertheless, convergence between the regions can be observed. Note that this is a property of the scenarios and that this is not necessarily a realistic assumption (Pritchett [26]). The pattern of industrial carbon dioxide emissions is similar to the pattern of income. Carbon dioxide emissions are projected to increase considerably. Some convergence is noticeable, but regional differences remain large.

[5] This assumption has been verified (for the base case assumptions and a limited set of alternative assumptions) in a grid search without endogenous stopping rule.

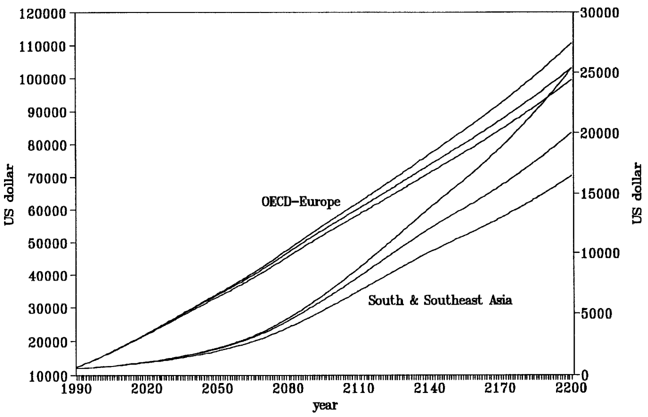

Figure 2. Income per capita (in US dollars) in OECD-Europe (left axis) and South and South-East Asia (right axis), 1990–2200, for the potential growth (top line), potential growth plus conventional air pollution (middle line) and business as usual scenarios (bottom line). Air pollution and climate change reduce per capita income.

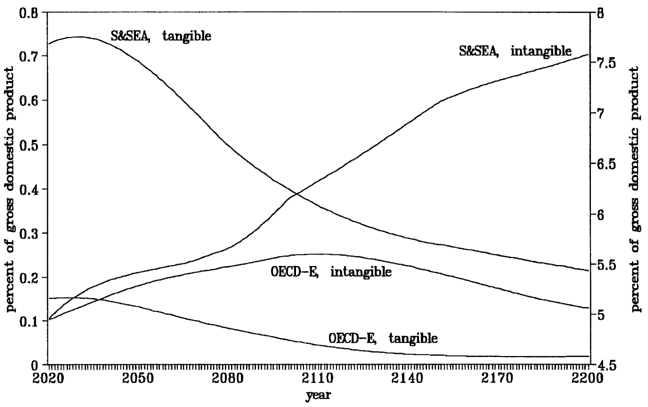

Figure 3. Tangible and intangible damage of climate change (in per cent of GDP) for OECD-Europe and South and South-East Asia for the business as usual scenario, 2020–2200. Intangible damage in S&SEA is on the right y-axis.

Figure 3 displays the tangible and intangible damages due to the enhanced greenhouse effects for OECD-Europe and South and South-East Asia for the business as usual scenario, including air pollution and, of course, climate change. The period 1990–2019 is not displayed as decision makers are assumed not to be able to influence the damage in this period; actual damages are distorted during this time because of the assumption that damage is zero in 1990. Tangible damages fall over time, as briefly outlined above. Main influences are the share of agriculture in GDP, and the number of immigrants. In OECD-Europe, intangible losses rise at first, but start falling in the 22nd century. The reason is that, as a function of the level of change, decreased cold stress slightly outweighs increased heat stress.[6] In addition, the pace of climate change gradually levels off, because population growth, economic growth and emission intensity slowly decline, and the atmosphere gets radiatively satiated. In South and South-East Asia, intangible damages keep increasing. Intangible damage is strongly pushed upwards by the increase in per capita income, but pushed downwards by decreasing vulnerability for malaria and emigration.

[6] Heat stress figures are based on Kalkstein and Tan [11], which is an update of Kalkstein [10]. Cold stress estimates have not been updated. A more serious problem is that, in *FUND*, there is no upper limit to the avoided cold stress deaths. However, this specification does not affect optimal emission control in a notable way. So, a solution to this potential problem is postponed to future work.

3.2. No regret

No regret policies can be undertaken for two reasons. Firstly, the economic benefits of emission reduction can lead regions to abate carbon dioxide emissions. Secondly, avoided conventional air pollution can be a reason for abatement. Table 8 displays the optimal emission abatement in case both air pollution damage and climate change are set to nought, and in case only climate change is set to nought. The economic benefits of emission control are clearly small and not a substantive cause for action. Conventional air pollution, however, is a reason to abate greenhouse gas emissions. Note that the optimal emission control is small. The figures in table 8 roughly equal the per cent emission reduction in 1991 (1990 remains uncontrolled), relative to the baseline. The expenditure on emission control is two orders of magnitude below 1% of GDP. Bottom-up emission control is higher, because abatement is cheaper in this parameterization.

3.3. Non-cooperative optimal abatement

As outlined above, the Nash–Cournot optimum is iteratively calculated. Convergence is rapid under the base case assumptions. In the top-down parameterization, only one iteration is needed, that is, each region reaches its optimum regardless of the behaviour of the other region. In the bottom-up parameterization, only one iteration is needed for all regions but South and South-East Asia and Africa. These two regions abate a little bit more when learning of the other regions' reduction plans. This so-called 'assurance' behaviour (Sen [28,29]) is also observed in earlier versions of *FUND* (Tol et al. [32]), but only in exceptional cases. The explanation is twofold. Firstly, more reduction elsewhere means less damage in the own region, implying a higher economic growth and more capacity and need to reduce emissions. Secondly, the global mean temperature is logarithmic in the concentration of carbon dioxide. Depending on the specification of the damage function, the higher the base concentration, the less damage one additionally emitted tonne of carbon causes.

Joint implementation is a popular manner to increase the efficiency of greenhouse gas emission control (Kuik et al. [13]). Given certain national emission targets, international reallocation of emission reduction helps a cost-effective solution. Joint implementation can readily be analyzed with *FUND*. In *FUND*, joint implementation is only allowed after all regions have taken measures as under Nash–Cournot. As such, joint implementation does not

Table 8
No regret emission control; percentage reduction from baseline in the 1990s.

Region	Negative costs		Air pollution	
	Top-down	Bottom-up	Top-down	Bottom-up
OECD-A	0.00	0.02	0.07	0.28
OECD-E	0.00	0.02	0.03	0.20
OECD-P	0.00	0.02	0.00	0.10
CEE&fSU	0.00	0.02	0.05	0.40
ME	0.00	0.02	0.28	0.18
LA	0.00	0.00	0.00	0.04
S&SEA	0.00	0.00	0.02	0.28
CPA	0.00	0.00	0.47	0.86
AFR	0.00	0.00	0.08	0.06
World	0.00	0.01	0.10	0.33

Source: own calculations.

Table 9
Non-cooperative emission control; percentage reduction in the 1990s.

Region			With joint implementation	
	Top-down	Bottom-up	Top-down	Bottom-up
OECD-A	0.07	0.28	0.07	0.28
OECD-E	0.03	0.20	0.03	0.20
OECD-P	0.00	0.10	0.00	0.10
CEE&fSU	0.05	0.40	0.05	0.42
ME	0.25	0.16	0.26	0.18
LA	0.00	0.04	0.00	0.04
S&SEA	0.02	0.26	0.02	0.28
CPA	0.53	0.96	0.56	1.00
AFR	0.07	0.06	0.08	0.06
World	0.12	0.34	0.11	0.35

Source: own calculations.

come in place of, but in addition to domestic action, in the spirit of international agreements. Note that in this specification, joint implementation influences efficacy rather than efficiency. Table 9 displays the outcomes, for both the top-down and the bottom-up parameterizations. Optimal emission control increases only slightly compared to the situation without joint implementation. OECD-America and South and South-East Asia invest in emission reduction in other regions, as additional domestic emission reduction is too expensive compared to the gains of reduced climate change. Table 10 displays the capital transfers, which are modest.

3.4. Cooperative optimal abatement

In the cooperative game, the sum of the regional net present welfares is optimized. In the top-down parameterization, the emission abatement effort of OECD-America, OECD-Europe, Central and Eastern Europe and the former Soviet Union, the Middle East, Centrally Planned Asia and Africa is higher than under non-cooperation (cf. table 11). However, except for the Middle East and Africa, these regions actually lose from cooperation, and so they leave the global coalition. Upon realizing this, it no longer pays for the Middle East and Africa either to abate more than under non-cooperation.

In the bottom-up parameterization, all regions, except Latin America and Africa, abate more under cooperation than under non-cooperation (cf. table 11). However, OECD-America, OECD-Europe, Central and Eastern Europe and the former Soviet Union and Centrally Planned Asia immediately leave the coalition as that is in their benefit. Upon realizing this, OECD-Pacific and the Middle East follow, and the situation is back to non-cooperation again.

So, international capital transfers are needed to ensure cooperation between the regions. Although global welfare is higher in the cooperative case than in the non-cooperative case, the benefits cannot be allocated such that the losers of cooperation are compensated by the winners. The reason is that welfare itself is not transferrable from one region to another. Money is, but welfare is convex in per capita income while the winners of cooperation are the vulnerable poor. Their welfare gain from cooperation when translated into money means little to the rich, at least not enough to

Table 10
Interregional capital transfers; billion US dollars.[a]

Region	Non-cooperation		Cooperation	
	Top-down	Bottom-up	Top-down	Bottom-up
OECD-A	−26.2	−22.9	201.7	485.0
OECD-E	0	0	−90.2	−70.3
OECD-P	0	0	−51.1	−143.8
CEE&fSU	0	13.6	118.0	223.7
ME	3.3	22.9	−18.3	−51.5
LA	0	0	−55.7	−157.7
S&SEA	−31.7	−71.2	−81.1	−230.6
CPA	50.7	57.6	4.8	25.0
AFR	4.0	0	−28.1	−79.7

[a] Negative numbers indicate that the region invests in other regions; numbers need not add up to zero due to rounding.

compensate for their loss from cooperation.

A different route is therefore taken. The non-cooperative solution is chosen as the point of departure. Additional carbon emission reduction measures are considered and evaluated as to their effect on global welfare. For measures which improve global welfare, it is investigated whether the losing regions (if any) can be compensated by the winning regions.

Additional measures are limited under the base case assumptions of *FUND*. OECD-America and Central and Eastern Europe and the former Soviet Union abate a little bit more of carbon (cf. table 11). Compensatory capital flows to these two regions, and to Centrally Planned Asia (which, like CEE&fSU, is above concluded to be a large winner in agriculture, provided climate does not change too fast). Table 10 displays the capital transfers. The capital transfers in the cooperative game differ markedly from the capital transfers under non-cooperation. First of all, capital flows are much larger in case of cooperation, and all regions are involved. A more important change is that OECD-America changes from a net investor in the non-cooperative game to a net receiver in the cooperative game. The explanation is that OECD-America is a very effective place to reduce carbon dioxide emissions, particularly in the shorter term. Under non-cooperation, none of the individual regions has either the interest or the capital to convince OECD-America to abate more, but jointly the other regions do. In the non-cooperative game, OECD-America invests in joint implementation because it has a limited interest in climate change, and abatement is cheaper overseas.

3.5. Evaluation

Figure 4 displays the global mean temperature for the years 1990–2200 for the business-as-usual and the non-cooperative optimal emission control scenarios. Welfare maximization does not call for drastic limitation of climate change. In the bottom-up parameterization, emissions are stricter controlled than in the top-down parameterization, because emission control is cheaper. Cooperative emission

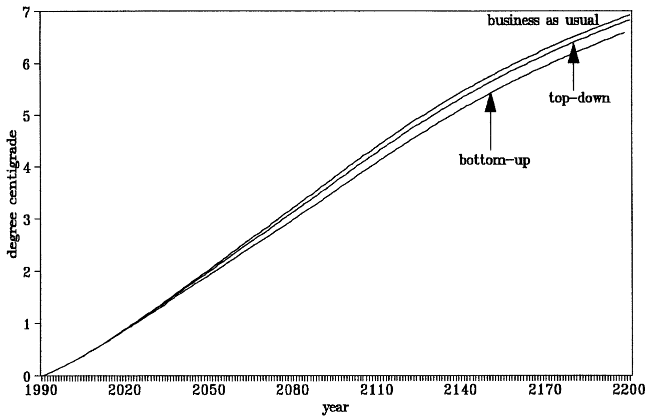

Figure 4. Global mean temperature (in degree centigrade) for the business as usual scenario and the non-cooperative (Nash–Cournot) emission control scenarios, for the top-down and bottom-up parameterizations.

control deviates only slightly from non-cooperative emission control; its consequences for climate change are therefore not displayed. Cooperative and non-cooperative emission control do not lie too far apart for four reasons. Firstly, the regions of *FUND* are large. Therefore, a substantial share of the benefits of emission reduction are internalized. Secondly, conventional air pollution, a regional problem, is a major reason to abate emissions. Thirdly, assurance behaviour is observed in the non-cooperative case. Fourthly, even in the cooperative case, emission abatement is modest.

4. Sensitivity analysis

Figures 5 and 6 display the sensitivity of non-cooperative optimal carbon dioxide emission abatement for OECD-Europe and South and South-East Asia for the bottom-up parameterization to a selection of the parameters of *FUND*.

Optimal emission abatement is sensitive to the driving forces, particularly to economic growth, autonomous carbon and energy efficiency improvements, and air pollution. The costs of emission reduction and the discount rate are also important. Optimal abatement goes down if the discount rate goes up, because the relative weight of the up-

Table 11
Cooperative emission control; percentage reduction in the 1990s.

Region	Global optimum[a]		With capital transfers	
	Top-down	Bottom-up	Top-down	Bottom-up
OECD-A	0.10	0.38	0.08	0.32
OECD-E	0.07	0.28	0.03	0.22
OECD-P	0.00	0.14	0.00	0.10
CEE&fSU	0.07	0.52	0.06	0.44
ME	0.26	0.18	0.25	0.16
LA	0.00	0.04	0.00	0.04
S&SEA	0.02	0.28	0.02	0.26
CPA	0.58	1.04	0.53	0.96
AFR	0.08	0.06	0.07	0.06
World	0.14	0.42	0.11	0.36

[a] Note that the global maximum implies that some regions lose compared to the non-cooperative solution.
Source: own calculations.

Table 12
Non-cooperative optimal emissions and emission control expenditures in 2000.

Region	Industrial CO_2 emissions[a]			Expenditure[b]	
	Business as usual	Top-down	Bottom-up	Top-down	Bottom-up
OECD-A	24.29	23.69	21.97	0.005	0.014
OECD-E	19.91	19.67	18.33	0.002	0.006
OECD-P	33.05	33.05	32.18	0.000	0.001
CEE&fSU	7.04	6.73	4.66	0.005	0.031
ME	46.24	44.05	44.85	0.040	0.028
LA	34.79	34.79	34.54	0.000	0.001
S&SEA	37.98	37.85	36.31	0.002	0.019
CPA	36.49	32.56	29.87	0.150	0.232
AFR	49.85	49.36	49.43	0.003	0.003
World	24.89	24.06	22.48	0.007	0.017

[a] Growth in industrial carbon dioxide emissions by the year 2000, compared to 1990, in per cent of 1990 emissions.
[b] Expenditure on emission control in the year 2000 as per cent of GDP in 2000.
Source: own calculations.

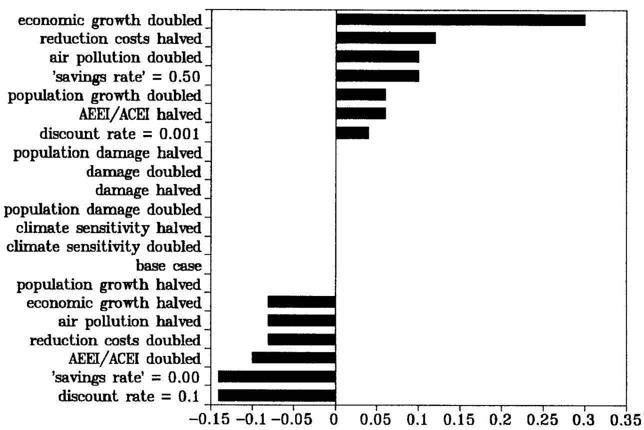

Figure 5. Sensitivity of bottom-up optimal emission control (% reduction in the 1990s) in OECD-Europe for 21 cases (indicated on the y-axis) in deviation from the base case.

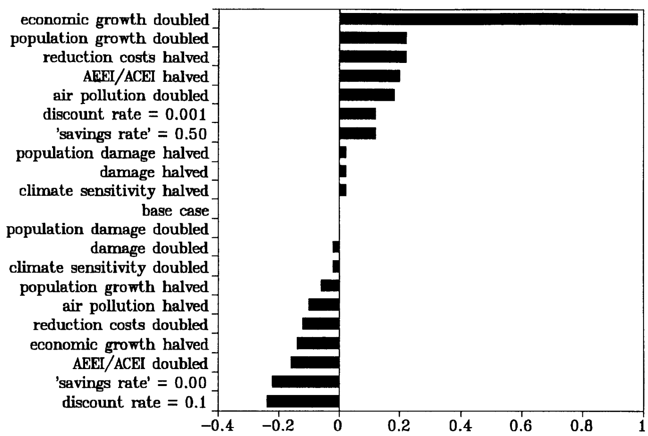

Figure 6. Sensitivity of bottom-up optimal emission control (% reduction in the 1990s) in South and South-East Asia for 21 cases (indicated on the y-axis) in deviation from the base case.

front mitigation costs goes up. Optimal abatement goes up if the discount rate goes down, but this effect is less pronounced than one might have expected, because there still is a trade-off between slowing economic growth, sooner (through emission abatement) and later (through climate change).[7] The costs of forestry measures have to be decreased by a factor twenty (!) to let regions implement this option. Optimal abatement is little sensitive to climatic change and its impact, although it is to the way in which impacts work through to the economy (savings' rate).

5. Conclusion

The analyses of this paper provide a tentative answer to the questions whether and (if so) how much and where to abate anthropogenic greenhouse gas emissions, so as to limit climatic change. This section summarizes the answer obtained with *FUND*, and compares them to findings in the literature.

Firstly, should we abate anthropogenic greenhouse gas emissions? The answer to this question is an unambiguous yes. This answer is not restricted to *FUND*; it is shared by all other cost–benefit analyses of climate changes, the most prominent of which are *DICE*, *CETA*, and *MERGE*. The argument is simple: as climate change causes damage, it pays to reduce climate change (cf. Weyant et al. [35], for a further discussion).

Secondly, how much greenhouse gas emissions should we abate? Table 12 displays the industrial carbon dioxide emissions in the year 2000, relative to 1990, for the business as usual scenario and top-down and bottom-up optimal control under non-cooperation (cf. table 8). It also shows the expenditure on emission reduction in that year. Under the base case assumptions, we should abate some greenhouse gas emissions, but not that much. The optimal strategy results in a reduced warming between 0.10°C (top-down, non-cooperation) and 0.35°C (bottom-up, cooperation) of a degree centigrade by the year 2100, close to the findings of *DICE*, *CETA*, and *MERGE*.[8] This is remarkable, since the damage module of *FUND* is very different from the damages in *DICE*, *CETA*, or *MERGE*. However, *FUND* includes secondary benefits of emission reduction and *FUND*'s discount rate is much lower. This suggests that, should the discount rate be equalized and the secondary benefits excluded, *FUND* favours lower emission reduction than *DICE*, *CETA*, and *MERGE*. The prime reason for this lies in the different specification of the climate change impact module in *FUND*, which results in much lower damages (cf. figure 3). For this reason, and because of the secondary benefits, the observed assurance behaviour and the size of the regions, *FUND*'s cooperative solution lies very close to its non-cooperative solution.

Thirdly, where should we abate greenhouse gas emissions? The answer to the question depends on one's perspective. A major reason to abate carbon dioxide emissions is the conventional air pollution avoided. This suggests that emissions should be abated domestically. Climate change mainly impacts on the poor, so it is in their interest to cut their emissions. Emission reduction has a larger effect in the regions which currently emit a lot, but is cheaper in the poorer regions.

The answers obtained by *FUND* and other models are only the first step of a long and arduous journey. Obvious extensions of the work presented in this paper are to look deeper into coalition formation, to extend the one-shot decisions to repeated games, and to repeat the exercises under uncertainty. Based on these first analyses, it appears that the goals set out in the Framework Convention of Climate Change (emission stabilization at the short term, concentration stabilization on the longer term) are too ambitious to maximize welfare. However, it also appears that current (close to absent) and no-regret policies are too little.

[7] Note that *FUND* cannot tinker with the savings' rate in the optimization.

[8] Note that the short term emission reduction is much lower, even though the reduced warming is about the same. This is explained from the fact that in *FUND* emissions are reduced by a permanent improvement in energy and carbon efficiency, whereas *CETA*, *DICE*, and *MERGE* lower emissions directly. Emission reduction in the long run is comparable, however.

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